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Original article



Using the Finite Element Method to Simulate a Carbon Fiber Reinforced Polymer Pressure Vessel

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Abstract

Introduction. Over the past decade, global demand for pressure vessels has increased significantly, specifically in such industries as aviation, space, chemical, and oil and gas. Being under the constant impact of high internal pressure, the walls of the tanks are under increased stress, which can cause their sudden destruction. To eliminate this probability and improve the strength characteristics, the tanks are made in the form of metal cylinders with an internal coating of composite material consisting of resin reinforced with carbon fibers. This article aimed at studying the effect of the angle of inclination of carbon fiber on cylindrical tanks and determining the maximum destructive pressure using the finite element method of ANSYS program.

Materials and Methods. Using the ANSYS program, a finite element model of a tank was created. It has a central part, which is a metal cylinder with an internal coating of composite material consisting of polymer reinforced with carbon fibers. At the ends of the tank, spiral wound hemispheres were placed. In these studies, SHELL 99 was used to model the layered composite material. The Tsai-Wu theory was used to determine the pressure tank failure criterion.

Results. The cylindrical tank model was calculated for two types of fiber winding paths: annular and spiral, at different angles of their inclination. The results of the pressure value analysis for different fiber inclination angles showed that, starting from the angle value of 0° and up to 45° , it increased, and then, up to the angle value of 65° , it began to decrease. The critical pressure value for a carbon fiber reinforced tank was 207 MPa, which was obtained at a fiber angle of 45° .

Discussion and Conclusion. Analysis of the studies showed that at a fiber inclination angle of 45° , the value of the maximum stress turned out to be the smallest, and the maximum possible destructive pressure at the same angle was 207 MPa. It follows, that the optimal fiber orientation angle to provide safe operation of the high-pressure tank is $\pm 45^\circ$, and the carbon fiber tank, calculated at the same fiber winding angle, has the maximum strength value.

Keywords: high-pressure tank, computer model, winding angle, composite coating, carbon fiber, polymer binder.

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Introduction. The use of high-pressure carbon fiber vessels has found widespread use in various industries due to its distinctive properties, such as low weight and high strength. Therefore, recently the demand for such vessels has increased significantly in cases where weight plays a major role [1, 2].

The critical areas of application of this type of tanks are aerospace, aviation, and chemical engineering. In addition, fiber-reinforced tanks are widely used for increase in pressure during the transportation of oil and gas. In many cases of such use, tanks are exposed to high internal pressure, which may result in a step-like increase in stress on the vessel walls and their sudden collapse, causing great damage to material and human resources [3, 4].

In [5], a number of studies were carried out aimed only at exploring a pressure tank made of multilayer composite, during which the expected collapse resistance was determined. In [6], the behavior of a rotating composite pressure vessel under the internal pressure and axial load was studied. In [7], the effect of thermal loads on a multilayer composite pressure tank was described. In [8], the behavior of a polygonal composite pressure tank of five different shapes under the action of internal pressure of various modes was studied; and in [9], the performance of a composite pressure tank was explored under the influence of transverse loads.

The design of a composite tank is a challenge; therefore, priority factors should be selected to conduct a complete and accurate analysis. We studied a pressure vessel reinforced with several layers of carbon fibers and subjected to internal pressure loading. To determine the maximum stresses and displacements at operating pressure, to identify the expected limiting pressure causing destruction, as well as to identify the optimal angle of orientation of the fibers, a finite element model of the tank was created using ANSYS customized application.

Materials and Methods. Theoretical Research. The high-pressure tank made of carbon fibre reinforced plastic (CFRP) consists of a central part, which is a metal cylinder with an internal coating made from a polymer reinforced with carbon fibers. The end surfaces of the tank have the shape of hemispheres with spiral winding (Fig. 1).



Fig. 1. Longitudinal section of the tank

Tanks operating at high pressures and reinforced with carbon fiber are manufactured by the method of filament winding (Fig. 2). To obtain the required reinforcement stability, the fibers are sent to a moving trolley with careful selection of their coordination, and then wound onto a cylindrical surface. The stability of fiber coordination is influenced by several factors: temperature, surface shape and treatment, as well as the degree of adhesion of fibers to the matrix. The winding angle is controlled by the speed of the trolley and the rotation speed of the cylindrical drum. To obtain high operational and strength properties, the inner cylindrical surface of the tank is covered with several layers of fibers [10].

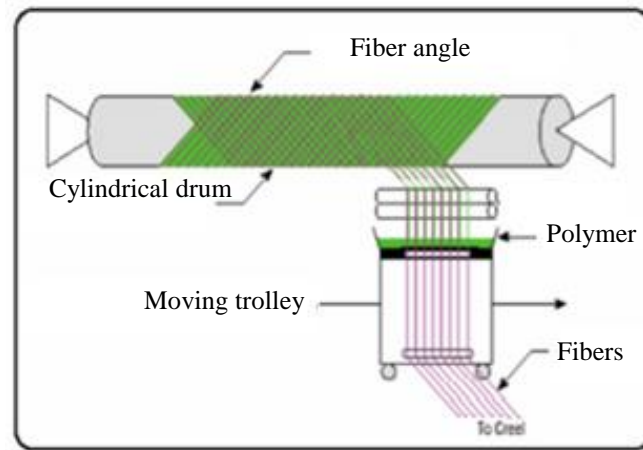


Fig. 2. Fiber winding scheme

The angle of the fibers has a significant effect on the properties of the vessels; therefore, to find the appropriate angle for each part of the vessel is of critical importance. The fiber orientation angle is determined by the required amount of friction between the fibers and the composite material layer, as shown in the relation:

$$\alpha(R) = \sin^{-1} \left(\frac{R_0}{R} \right) \pm \delta \left(\frac{R - R_0}{R_{t1} - R_0} \right)^n, \quad (1)$$

where R — distance between the center and the point of the layer; R_0 — central axis radius; R_{t1} — radius on the tangent to the surface of the cylinder at $\delta = 0$ [8].

Tsai-Wu Destruction Criteria. When studying and simulating a high-pressure tank made of composite material, the destruction criteria according to the Tsai-Wu theory [11] were used. The implementation of equation (1) is required to study the expected fracture of orthotropic materials according to the Tsai-Wu theory:

$$F_1\sigma_{11} + F_2\sigma_{22} + F_6\sigma_{12} + F_{11}\sigma_{22}^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_{11}\sigma_{22} = 1.$$

Elastic properties are determined by four independent constants: E_{11} , E_{22} , G_{12} , ν_{12} , presented in Table 1.

Table 1

Characteristics of LY5052/T300 composite material

Properties	Carbon fiber T300	Epoxide LY5052
Elasticity modulus	230 GPa	3.0 GPa
Tensile Strength	3.5 GPa	71.0 GPa
Density	1,760 g/cm ³	1.14 g/cm ³

Forces are calculated from the following equations:

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c}; F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}; F_6 = 0; F_{11} = -\frac{1}{X_t X_c};$$

$$F_{22} = -\frac{1}{Y_t Y_c}; F_{66} = -\frac{1}{S^2}; F_{12} = -\frac{1}{2} \sqrt{F_{11} F_{22}},$$

where X_t — tensile force in the longitudinal direction; Y_t — tensile force in the transverse direction; X_c — pressure force in the longitudinal direction; Y_c — pressure force in the transverse direction; S — shear force.

The maximum destructive stress is reached when one of the following ratios is met [12]:

$$\frac{\sigma_1}{X} \geq 1; \frac{\sigma_2}{Y} \geq 1; \frac{\tau_{12}}{S} \geq 1.$$

Material properties and finite element modeling. The composite material used for the tank under study is polymer reinforced with T300-type carbon fiber, and LY5052 epoxy is used as polymer material. Composite materials

are orthotropic in nature; therefore, the process of modeling them with finite elements is more complicated than isotropic materials, such as aluminum and steel.

Figure 3 shows a finite element model of a high-pressure tank made of carbon fiber, whose inner layer consists of an aluminum alloy reinforced with eight layers of Carbon/Epoxy T300/LY5052 composite material.

The model has the following dimensions:

- tank length — 1,200 mm;
- tank diameter in the center — 300 mm;
- total thickness — 64 mm;
- thickness of one layer — 6.5 mm;
- lining thickness — 0.12 mm.

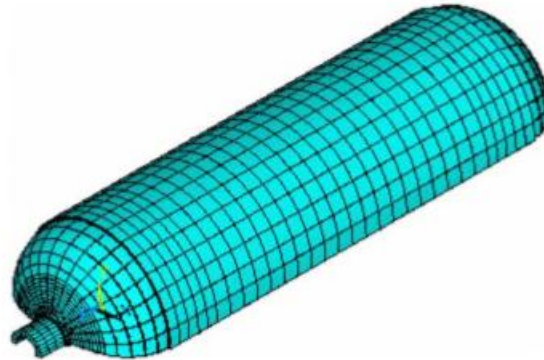


Fig. 3. Finite element model of the CFRP tank

To study high-pressure tanks made of composite materials, it is very important to select the appropriate type of finite elements. ANSYS program contains SHELL and SOLID finite elements required for modeling layered composite materials. For this study, SHELL 99 program was used, which accelerated the calculation of a structure with up to 250 layers. This element is a multi-level linear structure with eight nodes and six degrees of freedom. It allows the user to determine the flexibility, slope of layers, and density of each layer.

When studying composite materials, the formation of layers is one of the major issues, since each layer has its own angle of inclination, and the fibers in each layer have different angles of inclination; therefore, the properties of each layer should be determined separately.

The formation of layers requires the characteristics of the material, the number of layers, the fiber inclination angles, the thickness of the layer, and the number of integration points in each layer. Here is some comparative information about the properties of the materials used: CFRP and aluminum 6061. Density: CFRP — 1,570 kg/m³, aluminum — 2,750 kg/m³. Table 2 shows mechanical characteristics of the materials used: elastic modulus E ; shear strength G ; tensile strength V .

Table 2

Mechanical properties of CFRP and aluminum 6061

Parameters in the directions of coordinate axes, GPa	CFRP	Aluminum 6061
E_X	128	7070
E_Y	10.5	70
G_{XY}	5	70
G_{YZ}	5	
G_{ZX}	5	
V_{XY}	0.27	0.3
V_{YZ}	0.4	0.3
V_{ZX}	0.02	0.3

$[+25^\circ / -25^\circ]$, $[+30^\circ / -30^\circ]$, $[+35^\circ / -35^\circ]$, $[+40^\circ / -40^\circ]$, $[+45^\circ / -45^\circ]$, $[+50^\circ / -50^\circ]$, $[+55^\circ / -55^\circ]$.

Figure 4 shows a sequence of layers with the fiber inclination at an angle of $\pm 45^\circ$, implemented in ANSYS program.

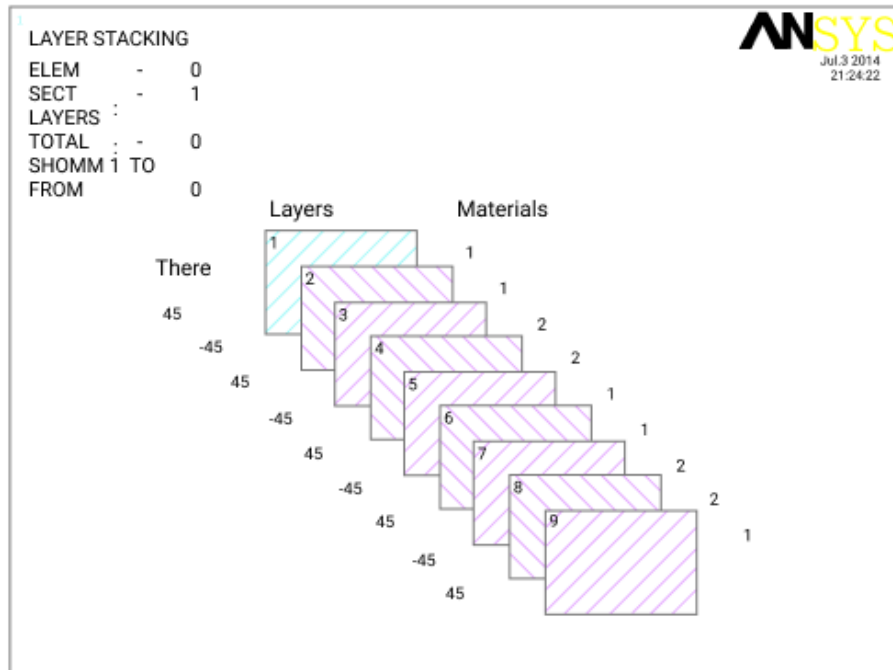


Fig. 4. Sequence of layers with the fiber inclination at an angle of $\pm 45^\circ$

Digital simulation. Calculation of stresses and displacements. The operation of the high-pressure tank was analyzed using the destruction criteria according to Tsai-Wu theory. Internal working pressure of 35 MPa was used to calculate the maximum stresses and displacements. The greatest stress of the tank was observed at the angle of inclination of the annular fibers — 0° and various angles of inclination of the spiral fibers:

$$[+25^\circ / -25^\circ], [+30^\circ / -30^\circ], [+35^\circ / -35^\circ], [+40^\circ / -40^\circ], [+45^\circ / -45^\circ], [+50^\circ / -50^\circ], [+55^\circ / -55^\circ].$$

Figure 5 shows the distribution of equivalent stresses and displacements in the tank at the fiber inclination of $\pm 45^\circ$. Tables 3, 4 show the maximum and minimum values of displacements and equivalent stresses in the directions of X, Y, Z coordinate axes.

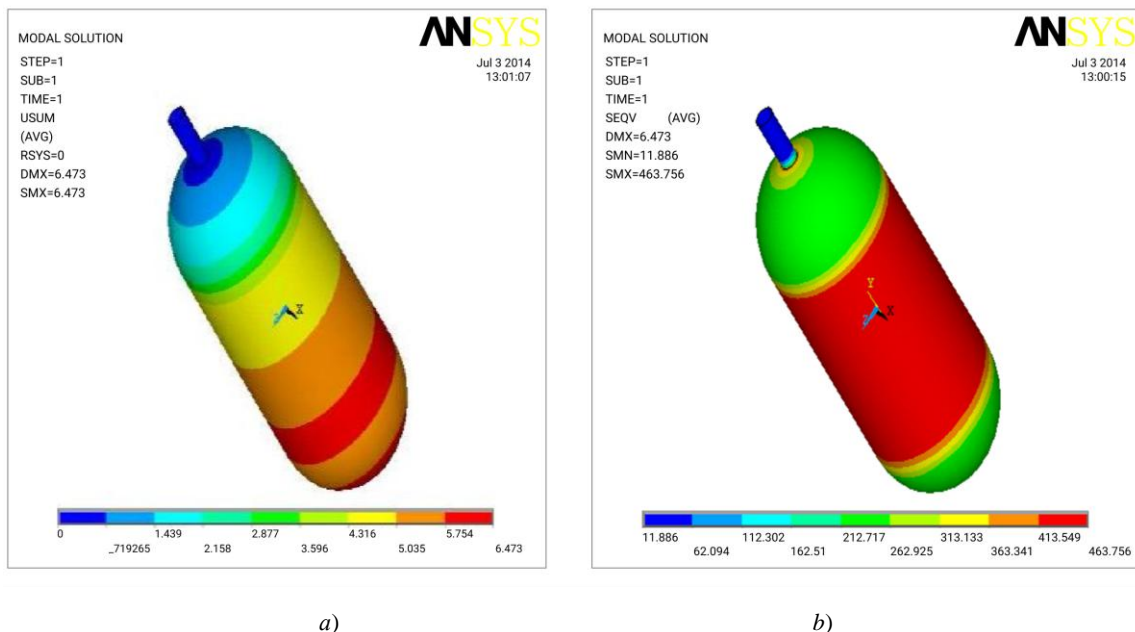


Fig. 5. Equivalent distribution in the tank: *a* — stresses; *b* — displacements

Table 3

Maximum and minimum displacement values
in the directions of X, Y, Z axes

Direction of deformation	Minimum, mm	Maximum, mm
total vector	0	6.473
along X-axis	-3.914	3.914
along Y-axis	-6.473	0
along Z-axis	-3.906	3.909

Table 4

Maximum and minimum stress values in the direction of X, Y, Z axes

Direction of deformation	Minimum, MPa	Maximum, MPa
total vector	11.886	463.756
along X-axis	-81.852	528.485
along Y-axis	-155.587	341.607
along Z-axis	-80.307	530.07

Determination of the expected destructive pressure and the optimal fiber inclination angle. The loading of the tank was carried out through gradually increasing the internal pressure, starting from its operating value — 35 MPa. Then, the obtained design maximum internal pressure stress was compared to the final allowable stress under the condition: $\sigma_{\max} \leq \sigma_u$, where: σ_{\max} — design maximum stress; σ_u — final allowable stress. The permissible stress for CFRP pressure tanks is 1,210 MPa.

The cylindrical tank model was calculated for two types of fiber winding paths: annular and spiral, as well as at different fiber inclination angles:

$$[+25^\circ / -25^\circ], [+30^\circ / -30^\circ], [+35^\circ / -35^\circ], [+40^\circ / -40^\circ], [+45^\circ / -45^\circ], [+50^\circ / -50^\circ], [+55^\circ / -55^\circ].$$

With an annular winding path, the fiber inclination angle to the axis of the cylinder was 0° . Figure 6 shows a finite element model of a cylindrical high-pressure tank.

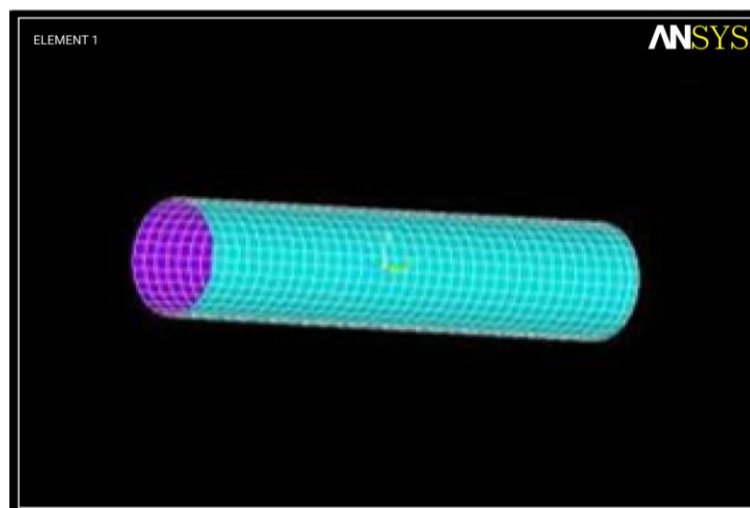


Fig. 6. Finite-element model of a cylindrical high-pressure tank

Research Results. Figure 7 shows the change in the maximum stress; starting from the angle value from 0° to 45° , it decreased, and then increased to the value of 65° . It was found that the maximum stress in a cylindrical CFRP pressure tank was the lowest at the fiber inclination angle of $\pm 45^\circ$.

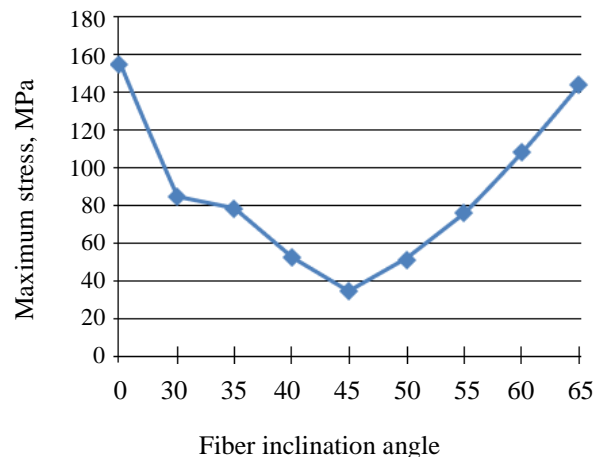


Fig. 7. Dependence of maximum stress on the fiber inclination angle

Figure 8 shows the results of the analysis of the pressure value for various fiber inclination angles: starting from the value of angle 0° and up to 45° , the pressure increased, and then it decreased to the value of angle 65° . The maximum pressure that a CFRP tank can withstand without destruction is 207 MPa. This pressure occurs at the fiber inclination angle of $\pm 45^\circ$, i.e., it is the expected value of the destructive pressure for the tank.

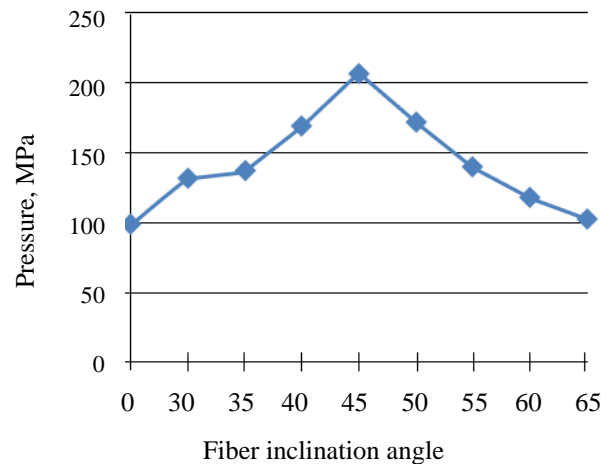


Fig. 8. Dependence of pressure on the fiber inclination angle

Figure 9 shows the distribution of stresses in the tank with fiber inclination angle of $\pm 45^\circ$, and the maximum pressure stress is 1,213 MPa, which is higher than the allowable stress for CFRP pressure tanks 1,210 MPa.

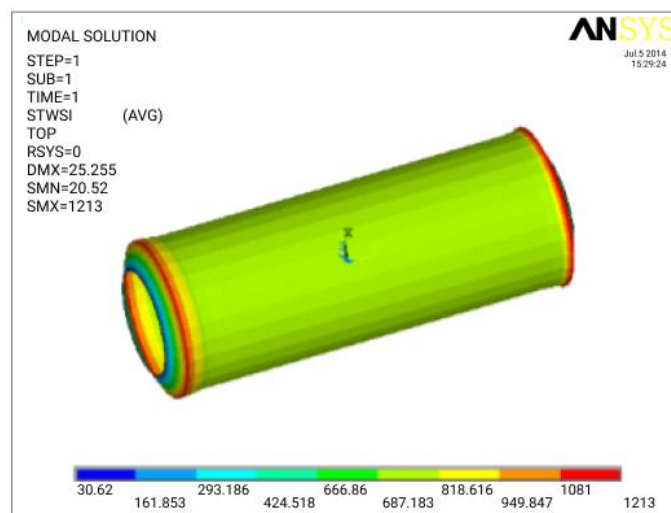


Fig. 9. Stress distribution in the tank under pressurization and at fiber angle of $\pm 45^\circ$

Discussion and Conclusions. A finite element model of a carbon fiber reinforced tank was designed and analyzed using ANSYS program with the application of SHELL 99 element in the course of the simulation process. Several models were created with different fiber angles. The maximum stress and collapse pressure for the high-pressure vessel were calculated using the Tsai-Wu criteria. It was found that the maximum stress was the smallest at the fiber inclination angle of $\pm 45^\circ$, and the maximum possible collapse pressure under the same conditions was 207 MPa. This indicates that the optimal fiber angle for safe operation of a pressure vessel is $\pm 45^\circ$, and a CFRP vessel rated at the same fiber winding angle has maximum strength.

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Claimed contributorship

I. R. Antipas: academic advising; research task setting; definition of research methodology; collection and analysis of the analytical and practical materials on the research topic; critical analysis and finalization of the solution; computer implementation of the problem solution. A. G. Dyachenko: analysis of scientific sources on the topic of research, critical analysis and revision of the text.

Conflict of interest statement

The authors do not have any conflict of interest.

All authors have read and approved.